INVESTIGATING THE MOBILITY OF LIGHT AUTONOMOUS TRACKED VEHICLES USING A HIGH PERFORMANCE COMPUTING SIMULATION CAPABILITY

Prof. Dan Negrut
Hammad Mazhar
Daniel J. Melanz
University of Wisconsin-Madison
Madison, WI

Dr. David Lamb
Dr. Paramsothy Jayakumar
Michael Letherwood
US Army TARDEC
Warren, MI

Dr. Abhinandan Jain
Dr. Marco Quadrelli
Jet Propulsion Lab
California Institute of Technology
Pasadena, CA

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **16 AUG 2012**	2. REPORT TYPE **Briefing**	3. DATES COVERED **01-07-2012 to 01-08-2012**
4. TITLE AND SUBTITLE **Investing the Mobility of Light Autonoumous Tracked Vehicles using a High Performance Computing Simulation Capability**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **David Lamb; Paramsothy Jayakumar; Michael Letherwood; Dan Negut; Abhinandan Jain**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army TARDEC,6501 East Eleven Mile Rd,Warren,Mi,48397-5000**		8. PERFORMING ORGANIZATION REPORT NUMBER **#23230**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000**		10. SPONSOR/MONITOR'S ACRONYM(S) **TARDEC** 11. SPONSOR/MONITOR'S REPORT NUMBER(S) **#23230**
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **Submitted to 2012 NDIA Ground Vehicle Systems Engineering and Technology Symposium August 14-16 Troy, Michigan**		
14. ABSTRACT **briefing charts.**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Public Release**	**51**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Acknowledgements

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MODELING AND SIMULATION, TESTING AND VALIDATION

- Collaborators:
  - Alessandro Tasora – University of Parma, Italy
  - Mihai Anitescu – Argonne National Lab, USA
  - Lab Students:
    - Aaron Bartholomew
    - Makarand Datar
    - Toby Heyn
    - Naresh Khude
    - Justin Madsen
    - Hammad Mazhar
    - Dan Melanz
    - Spencer O'Rourke
    - Arman Pazouki
    - Andrew Seidl
    - Rebecca Shotwell
- Financial support
  - National Science Foundation, Career Award
  - Army Research Office (ARO)
  - US Army TARDEC
  - FunctionBay, S. Korea
  - NVIDIA
  - Caterpillar
  - MSC.Software
  - Advanced Micro Devices (AMD)

Classical Computational Dynamics, Constrained Equations of Motion

Generalized Positions

Velocity Transformation Matrix

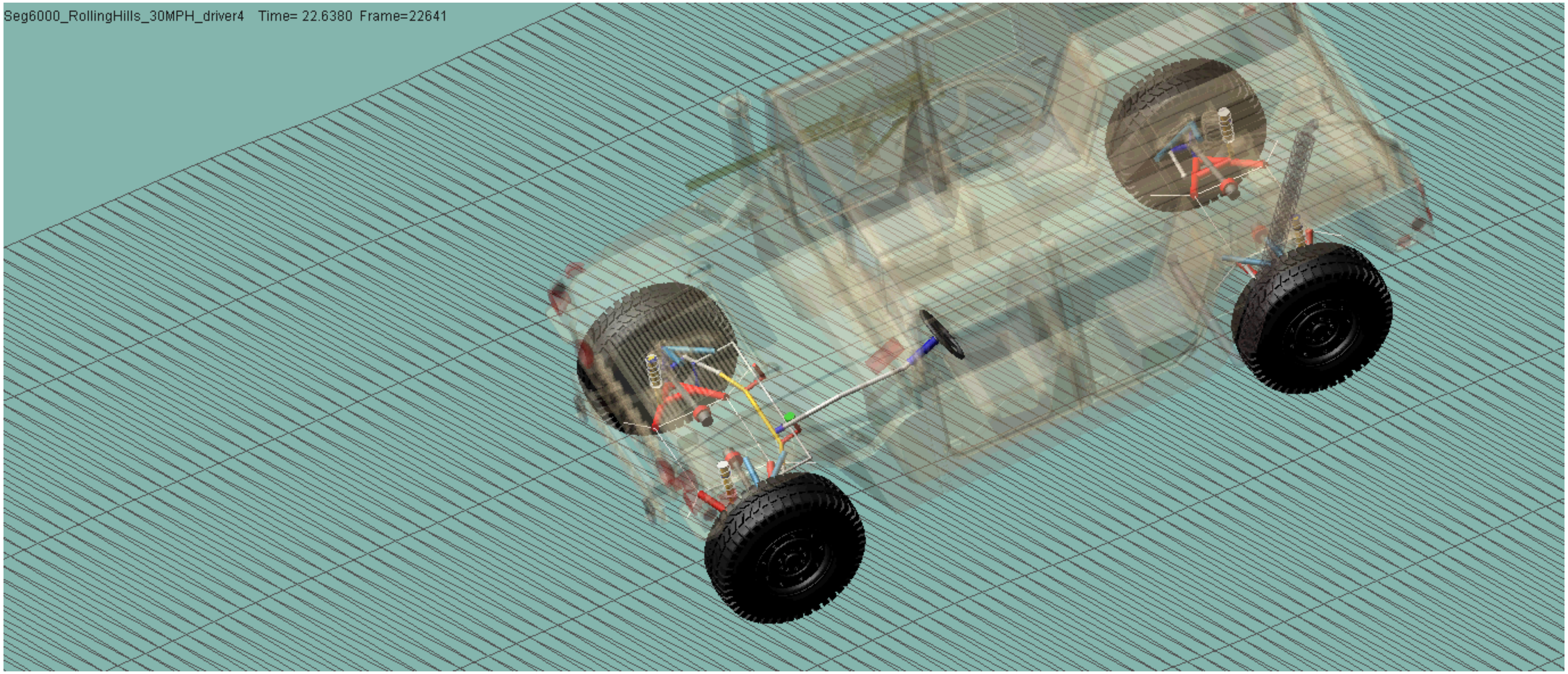
Generalized Mass Matrix

Generalized Velocities

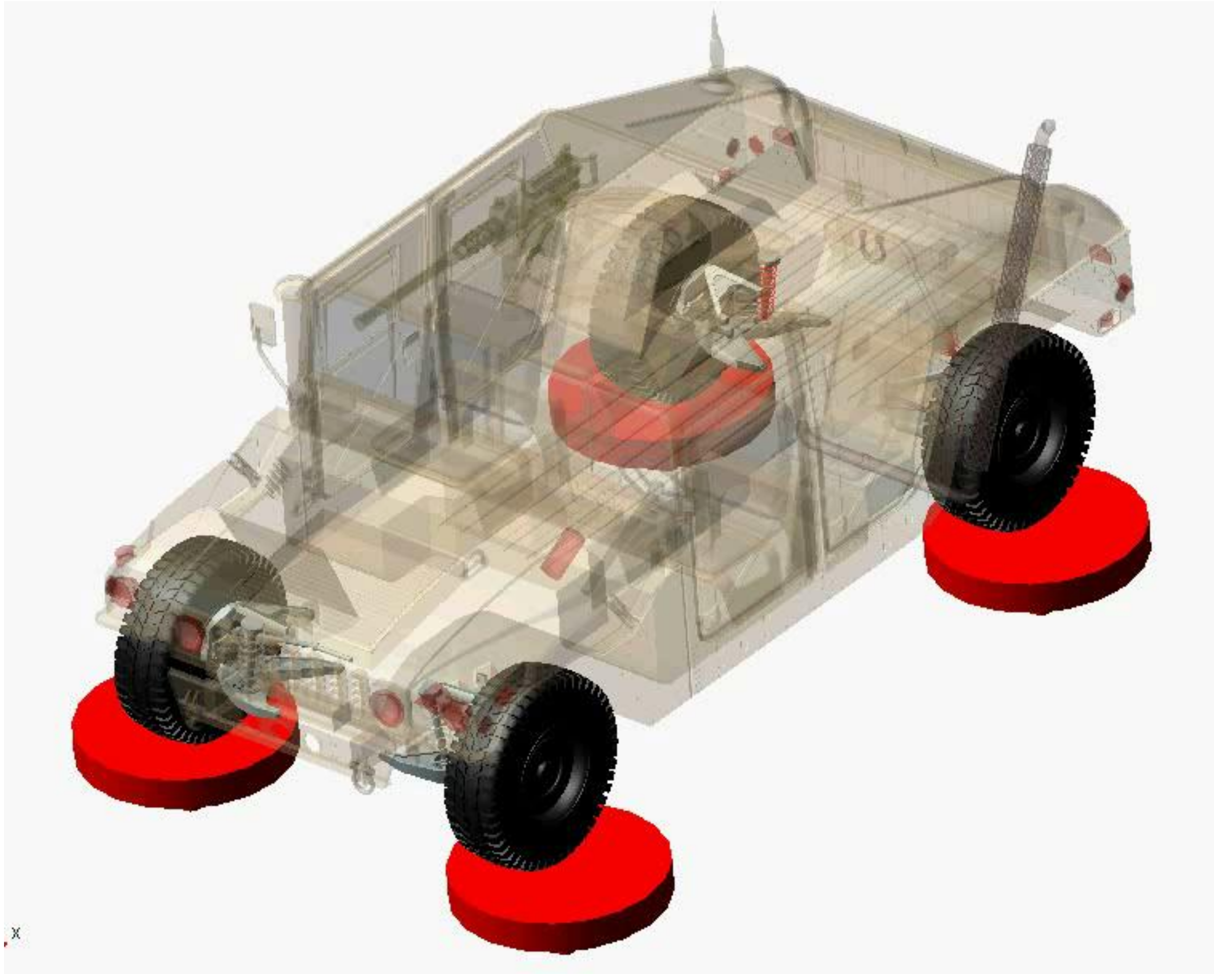
Kinematic Differential Equations	$\dot{\mathbf{q}} = \mathbf{L}(\mathbf{q})\mathbf{v}$
Force Balance Equations	$\mathbf{M}(\mathbf{q})\dot{\mathbf{v}} = \underbrace{\mathbf{f}(t,\mathbf{q},\mathbf{v})}_{\text{Applied Force}} - \overbrace{\mathbf{g}_{\mathbf{q}}^{T}(\mathbf{q},t)\boldsymbol{\lambda}}^{\text{Reaction Force}}$
Holonomic Kinematic Constraints	$\mathbf{g}(\mathbf{q},t) = \mathbf{0}$

Multibody Dynamics: Is anything left to do?

- **Purpose**: understand/optimize performance before building prototype



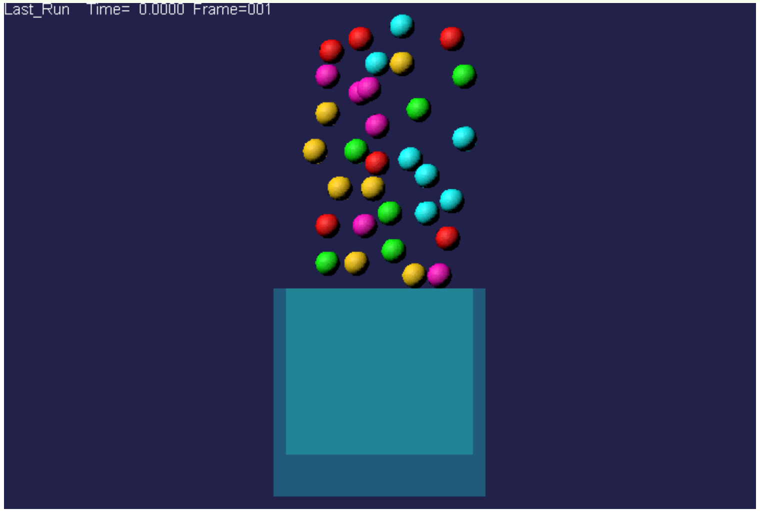
Multibody Dynamics: Is anything left to do?



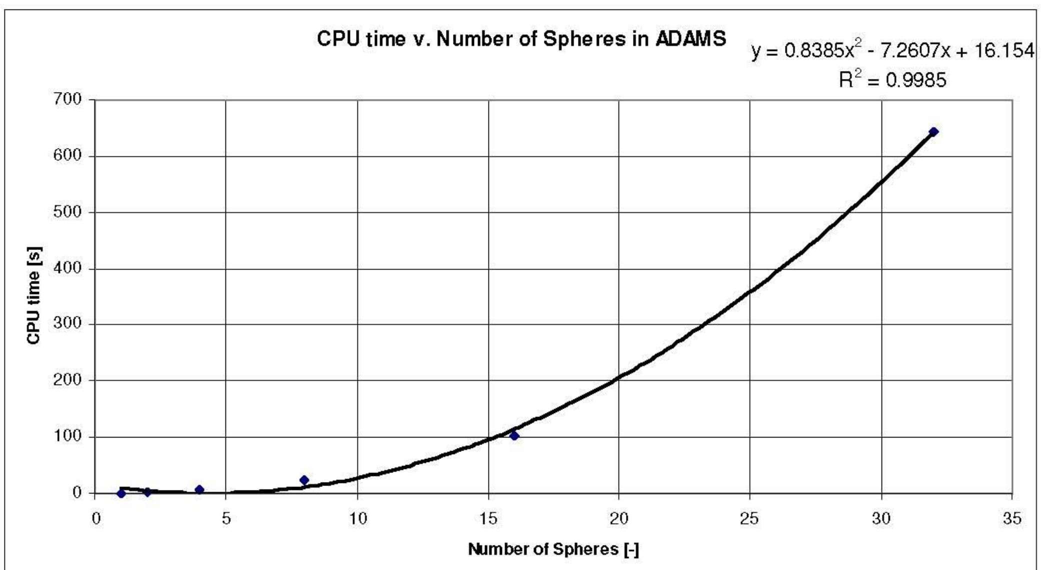
All the good music has already been written by people with wigs and stuff.

Frank Zappa

Frictional Contact Simulation
[Commercial Solution]



- Model Parameters:
  - Spheres: 60 mm diameter and mass 0.882 kg
  - Forces: smoothing with stiffness of 1E5, force exponent of 2.2, damping coefficient of 10.0, and a penetration depth of 0.1
  - Simulation length: 3 seconds



CAE: Looking Ahead…

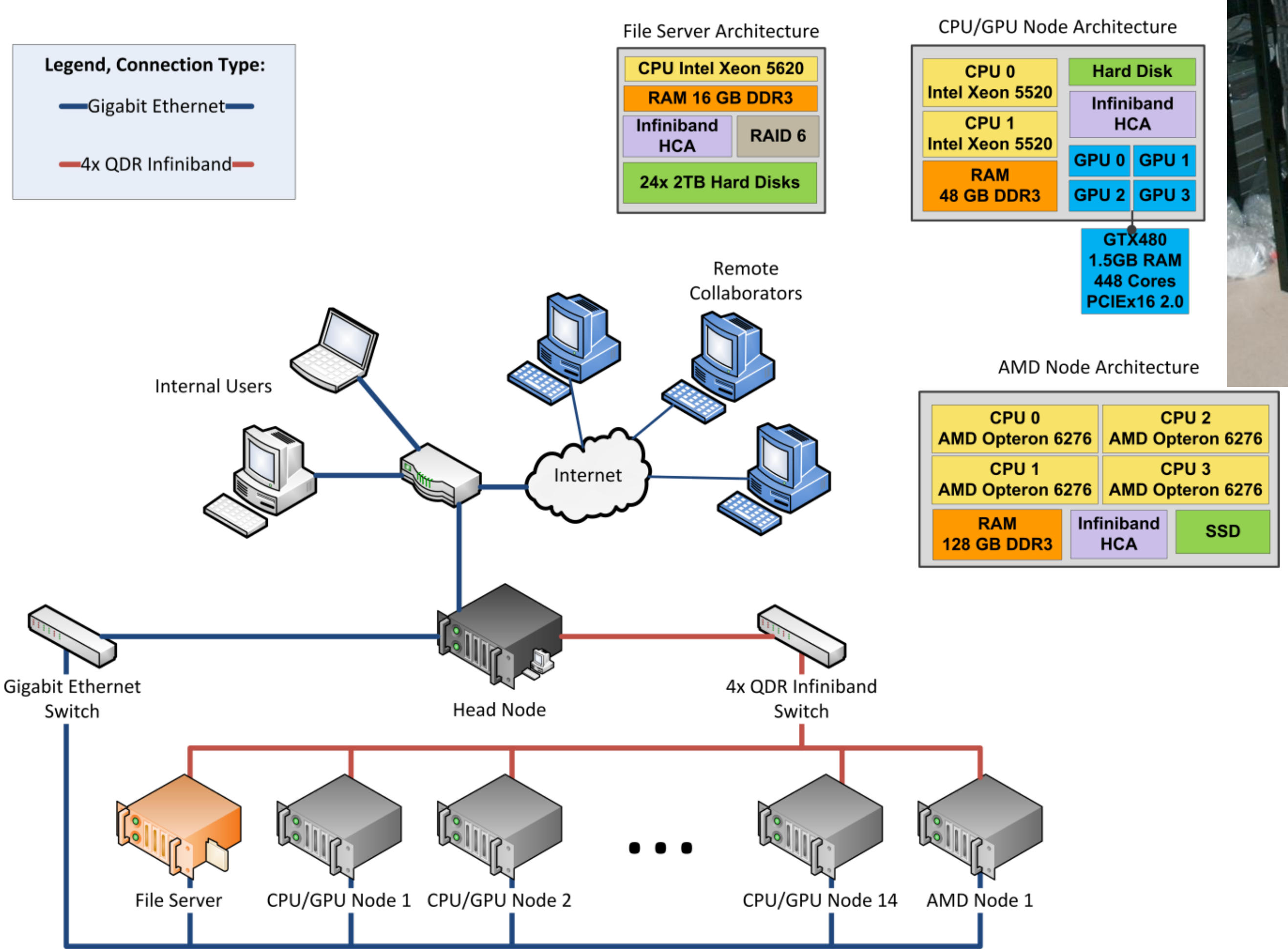
- How is the Rover moving along on a slope with granular material?
- What wheel geometry is more effective?

Multibody Dynamics: Lots to be done…

- Applications transitioning from multi-body to many-body dynamics
- Bodies interacting through friction/contact/impact
- Bodies are compliant, sometimes undergo large deformations
- Bodies might interact with fluid (FSI)
- Tomorrow’s problems are in the realm of multi-phsyics

Simulating large engineering problems remains a challenge…

Lab's Research Heterogeneous Computing Cluster



Lab's Research Heterogeneous Computing Cluster

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- More than 25,000 GPU scalar processors
  - Can manage about 75,000 GPU parallel threads at full capacity
- More than 1000 CPU cores
- Mellanox Infiniband Interconnect, 40Gb/sec
- About 0.7 TB of RAM
- More than 20 Tflops DP
- …

The issues is not hardware availability. Rather, it is producing modeling and solution techniques that can leverage this hardware

Heterogeneous Computing Template (HCT):

A Research-Grade Software Infrastructure for Large Scale Computational Dynamics Simulation

- Goal, lab's research effort: shape up the future of physics-based simulation
  - Develop a Heterogeneous Computing Template (HCT) that leverages emerging hardware architectures and suitable algorithms to solve open engineering problems
- Targeted "emerging hardware architectures" :
  - Clusters of CPUs and GPUs (accelerators)
    - More than 100 CPU cores, tens of GPU cards, tens of thousands of GPU cores
- Focus on "open engineering problems"
  - Vehicle mobility, granular dynamics, soil modeling, tire/terrain modeling, FSI, etc.

HCT: Five Major Components

- Computational Dynamics requires
  - Advanced modeling techniques
  - Strong algorithmic (applied math) support
  - Proximity computation
  - Domain decomposition & Inter-domain data exchange
  - Post-processing (visualization)

- HCT represents the library support, the associated API, and the embedded tools that support this five component abstraction

- Multi-Physics targeted Computational Dynamics requires
  - **Advanced modeling techniques**
  - Strong algorithmic (applied math) support
  - Proximity computation
  - Domain decomposition & Inter-domain data exchange
  - Post-processing (visualization)

HCT: Support for Advanced Modeling Techniques

- Modeling: what does it mean?
  - The process of formulating a set of governing differential equations that captures the multi-physics associated with the engineering problem of interest

- Modeling decisions are consequential
  - Good modeling places you at an advantage when it comes to simulating hard problems

Multi-Body Dynamics w/ DVI

Generalized Positions

Generalized Mass Matrix

Velocity Transformation Matrix

Generalized Velocities

Kinematic Differential Equations

$$\dot{\mathbf{q}} = \mathbf{L}(\mathbf{q})\mathbf{v}$$

Force Balance Equations

$$\mathbf{M}(\mathbf{q})\dot{\mathbf{v}} = \underbrace{\mathbf{f}(t,\mathbf{q},\mathbf{v})}_{\text{Applied Force}} - \overbrace{\mathbf{g}_{\mathbf{q}}^{\mathrm{T}}(\mathbf{q},t)\boldsymbol{\lambda}}^{\text{Reaction Force}} + \overbrace{\sum_{i=1}^{N_c}\left(\gamma_n^i \mathbf{D}_n^{T,i} + \gamma_u^i \mathbf{D}_u^{T,i} + \gamma_w^i \mathbf{D}_w^{T,i}\right)}^{\text{Frictional Contact Force}}$$

Holonomic Kinematic Constraints

$$\mathbf{g}(\mathbf{q},t) = \mathbf{0}$$

Contact Complementarity Conditions

$$0 \le \Phi^i(\mathbf{q},t) \perp \overbrace{\gamma_n^i}^{\text{Contact Impulse, for Contact "}i\text{"}} \ge 0 \qquad i = 1,2,\ldots,\underbrace{N_c}_{\text{Total Number of Contacts}}$$

Coulomb Friction Model

$$(\gamma_u^i, \gamma_w^i) = \operatorname*{arg\,min}_{\mu^i \gamma_n^i \ge \sqrt{(\gamma_u^i)^2 + (\gamma_w^i)^2}} \underbrace{\left(\gamma_u^i \mathbf{v}^T \mathbf{D}_u^i + \gamma_w^i \mathbf{v}^T \mathbf{D}_w^i\right)}_{\text{Friction Dissipation Energy}}$$

Gap Function, for Contact "i"

Friction Impulse Components, for Contact "i"

Traditional Discretization Scheme

positions

time step index

$$\boxed{\mathbf{q}}^{(l+1)} = \mathbf{q}^{\boxed{(l)}} + h\mathbf{L}(\mathbf{q}^{(l)})\mathbf{v}^{(l+1)}$$

Mass Mat.

speeds

Applied Forces

Reaction impulses

$$\boxed{\mathbf{M}}(\mathbf{v}^{(l+1)} - \boxed{\mathbf{v}^{l}}) = h\mathbf{f}(t^{(l)}, \mathbf{q}^{(l)}, \mathbf{v}^{(l)}) + \sum_{i \in \mathcal{A}(q^{(l)},\delta)} \left(\boxed{\gamma_{i,n}\, \mathbf{D}_{i,n}} + \boxed{\gamma_{i,u}\, \mathbf{D}_{i,u}} + \boxed{\gamma_{i,w}\, \mathbf{D}_{i,w}}\right)$$

$$i \in \mathcal{A}(q^{(l)},\delta): \quad 0 \leq \frac{1}{h}\Phi_i(\mathbf{q}^{(l)}) + \mathbf{D}_{i,n}^{T}\mathbf{v}^{(l+1)} \boxed{\perp} \gamma_n^i \geq 0,$$

Complementarity Condition

$$(\gamma_{i,u}, \gamma_{i,w}) = \underset{\mu_i \gamma_{i,n} \geq \sqrt{\gamma_{i,u}^2 + \gamma_{i,w}^2}}{\operatorname{argmin}} \quad \mathbf{v}^T \left(\gamma_{i,u}\, \mathbf{D}_{i,u} + \gamma_{i,w}\, \mathbf{D}_{i,w}\right).$$

Stabilization term

Coulomb 3D fricion model

(Stewart, 1998)

The Cone Complementarity Problem (CCP)

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- First order optimality conditions lead to Cone Complementarity Problem

- Introduce the convex hypercone...

$$\Upsilon = \left(\bigoplus_{i \in \mathcal{A}(\mathbf{q}^l, \epsilon)} \mathcal{FC}^i \right)$$

... and its polar hypercone:

$$\Upsilon^\circ = \left(\bigoplus_{i \in \mathcal{A}(\mathbf{q}^l, \epsilon)} \mathcal{FC}^{i\circ} \right)$$

$\mathcal{FC}^i \in \mathbb{R}^3$ represents friction cone associated with i^{th} contact

CCP assumes following form: Find γ such that

$$\gamma \in \Upsilon \perp -(\mathbf{N}\gamma + \mathbf{d}) \in \Upsilon^\circ$$

The Quadratic Programming Angle…

- The relaxed EOM represent a cone-complementarity problem (CCP)
- The CCP captures the first-order optimality condition for a quadratic optimization problem with conic constraints:

$$\begin{cases} \min \mathbf{q}(\gamma) = \frac{1}{2}\gamma^{\mathbf{T}}\mathbf{N}\gamma + \mathbf{d}^{\mathbf{T}}\gamma \\ \text{subject to} \quad \gamma_i \in \Upsilon_i \ \text{ for } \ i = 1, 2, \ldots, N_c \end{cases}$$

- Notation used:

$$\gamma \equiv [\gamma_1^T, \gamma_2^T, \ldots, \gamma_{N_c}^T]^T \in \mathbb{R}^{3 \times N_c} \qquad \text{and} \qquad \Upsilon_i : (\gamma_{u,i}^2 + \gamma_{w,i}^2) - \mu_i^2 \gamma_{n,i}^2 \leq 0$$

CCP Solution Algorithm
[mapped on the GPU]

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1. For each contact i, evaluate $\eta_i = 3/\text{Trace}(\,\mathbf{D}_i^T \mathbf{M}^{-1}\,\mathbf{D}_i)$.

2. If some initial guess γ^* is available for multipliers, then set $\gamma^0 = \gamma^*$, otherwise $\gamma^0 = \mathbf{0}$.

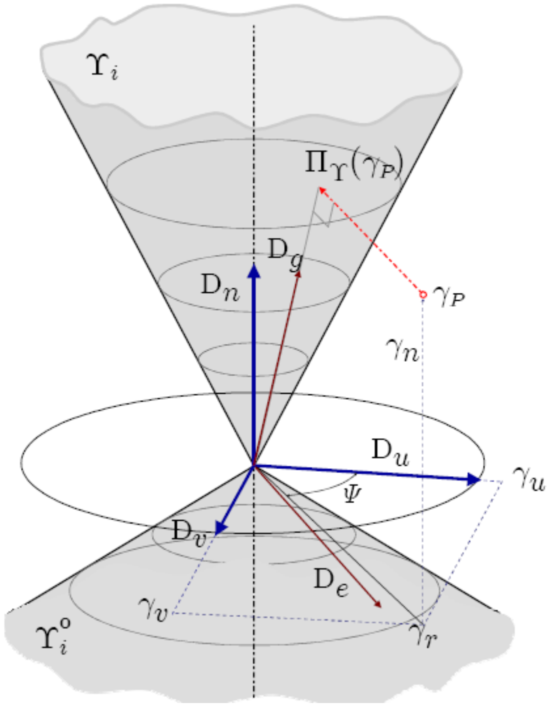
3. Initialize velocities: $\mathbf{v}^0 = \sum_i \mathbf{M}^{-1}\,\mathbf{D}_i \gamma_i^0 + \mathbf{M}^{-1}\tilde{\mathbf{k}}$.

4. For each contact i, compute changes in multipliers for contact constraints:

$$\gamma_i^{r+1} = \lambda\,\Pi_{\Upsilon_i}\left(\gamma_i^r - \omega\eta_i\left(\mathbf{D}_i^T\mathbf{v}^r + \mathbf{b}_i\right)\right) + (1-\lambda)\gamma_i^r\ ;$$

$$\Delta\gamma_i^{r+1} = \gamma_i^{r+1} - \gamma_i^r\ ;$$

$$\Delta\mathbf{v}_i = \mathbf{M}^{-1}\,\mathbf{D}_i\Delta\gamma_i^{r+1}.$$

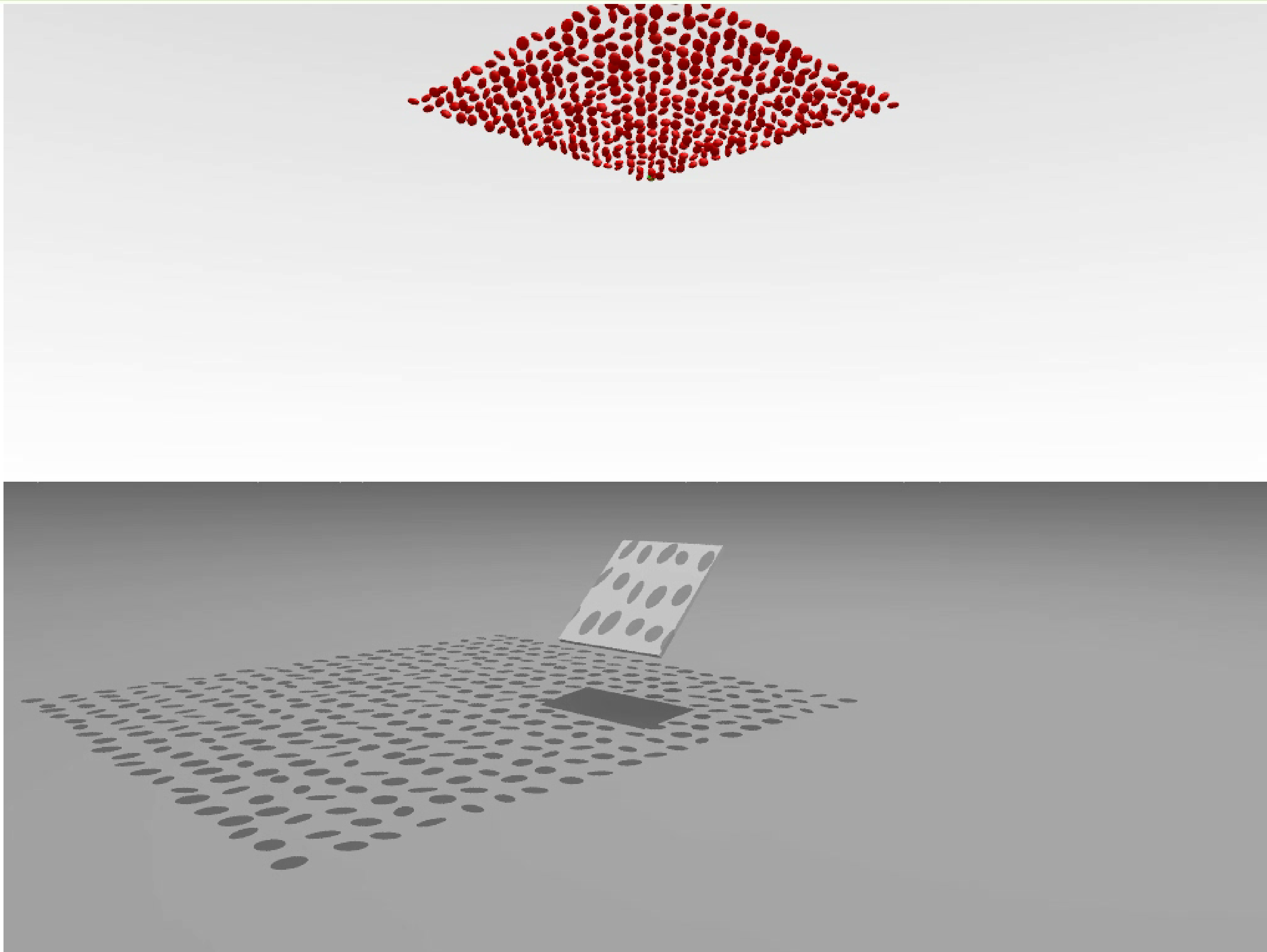


5. Apply updates to the velocity vector:

$$\mathbf{v}^{r+1} = \mathbf{v}^r + \sum_i \Delta\mathbf{v}_i$$

6. $r := r + 1$. Repeat from 4 until convergence or $r > r_{max}$

Mixing 50,000 M&Ms on the GPU



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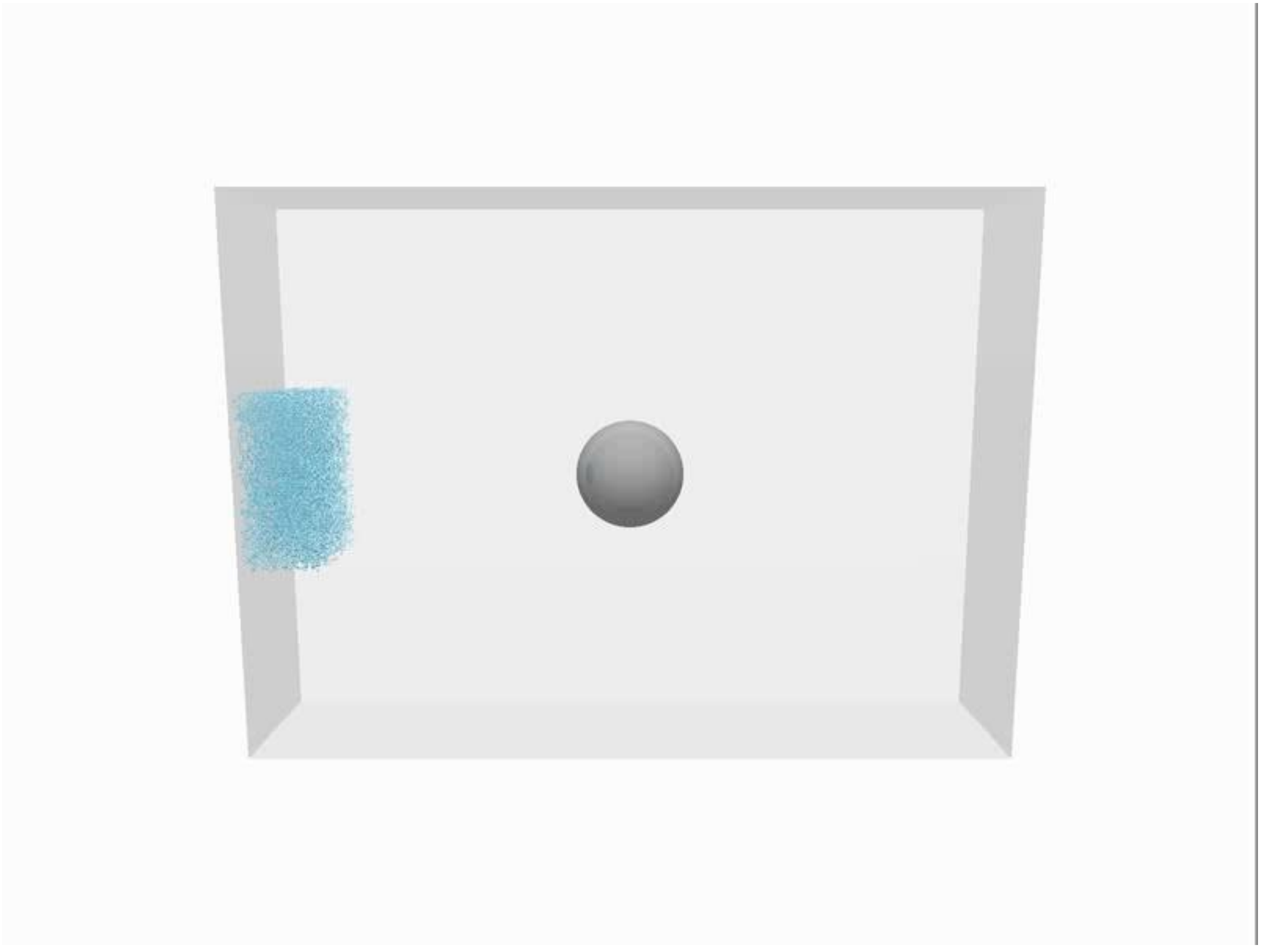
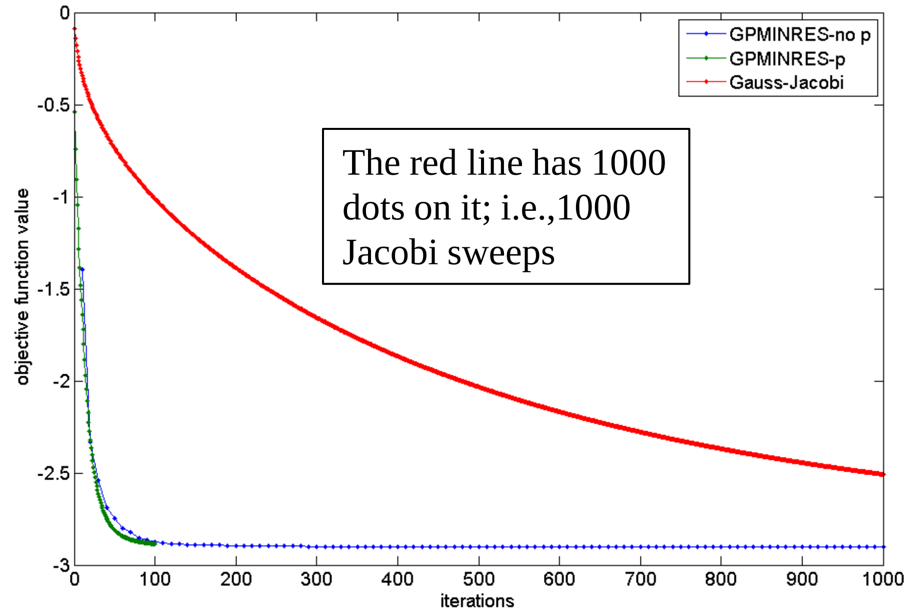
  - Advanced modeling techniques
  - **Strong algorithmic (applied math) support**
  - Proximity computation
  - Domain decomposition & Inter-domain data exchange
  - Post-processing (visualization)

1 Million Rigid Spheres
[parallel on the GPU]



Objective Function Value

[1K bodies, 3525 contacts]



The green & blue lines have 100 dots on them; i.e.,100 changes of active set

Method	Iterations	Final Objective Function Value	γ_{min}	γ_{max}	Computation Time [sec]
GPMINRES-no p	1000 MinRes Its. [within 100 changes of active set]	-2.9035	0.0	7.7487	6.7002
GPMINRES-no p (not plotted above)	10000 MinRes Its. [within 1000 changes of active set]	-2.9045	0.0	8.2002	61.0698
GPMINRES-p	100 MinRes Its. [within 100 changes of active set]	-2.8854	0.0	6.8551	1675
Jacobi	1000	-2.5077	0.0	4.4961	3.6643

- Multi-Physics targeted Computational Dynamics requires
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  - **Proximity computation**
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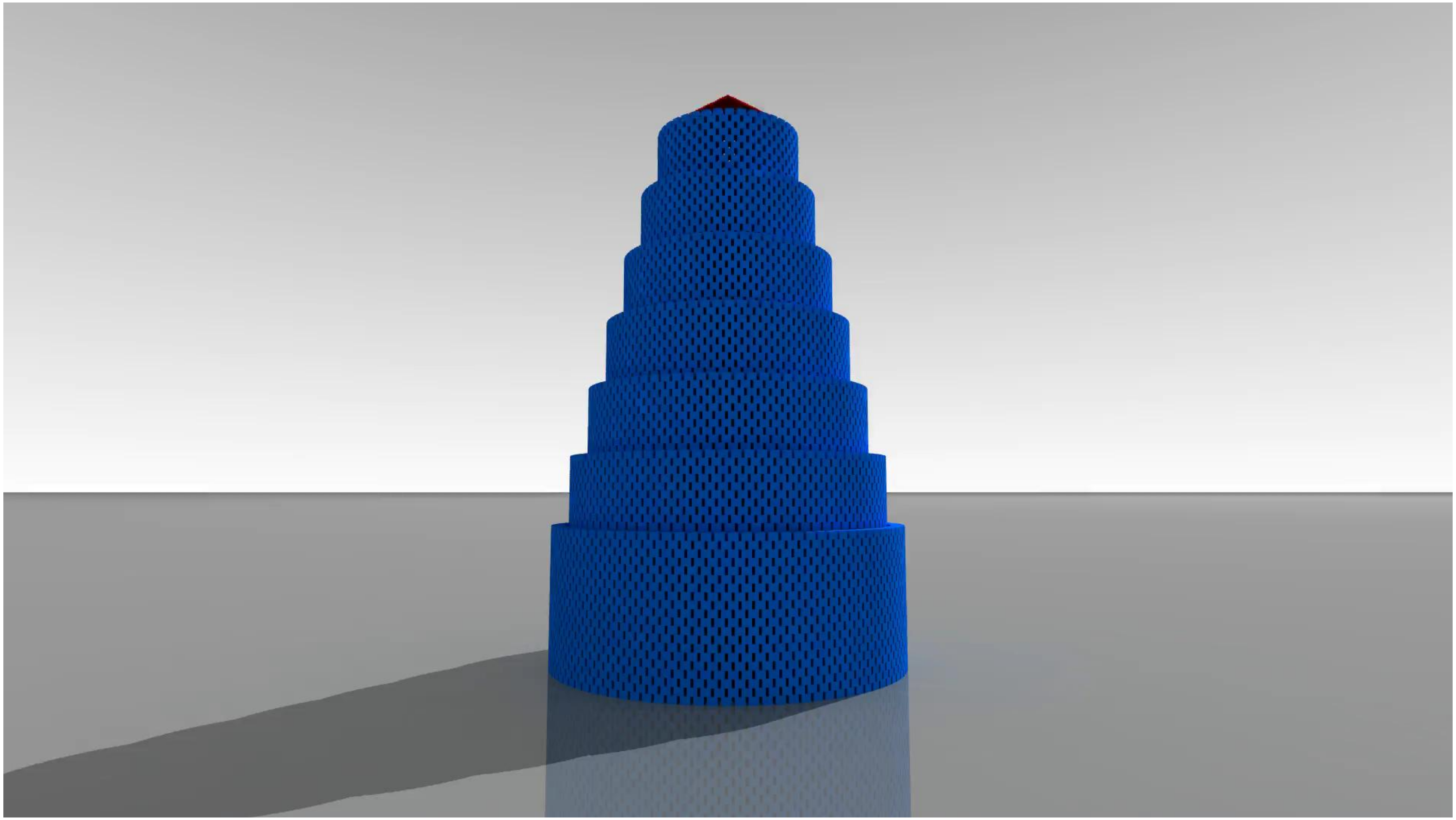
600,000 Bodies Moving & Colliding
[on the GPU]



Example: Ellipsoid-Ellipsoid CD

$$\mathbf{d} = \mathbf{P}_1 - \mathbf{P}_2 = \left(\frac{1}{2\lambda_1}\mathbf{M}_1 + \frac{1}{2\lambda_2}\mathbf{M}_2\right)\mathbf{c} + (\mathbf{b}_1 - \mathbf{b}_2)$$

$$\frac{\partial \mathbf{d}}{\partial \alpha_i} = \frac{\partial \mathbf{P}_1}{\partial \alpha_i} - \frac{\partial \mathbf{P}_2}{\partial \alpha_i} \quad , \quad \frac{\partial^2 \mathbf{d}}{\partial \alpha_i \partial \alpha_j} = \frac{\partial^2 \mathbf{P}_1}{\partial \alpha_i \partial \alpha_j} - \frac{\partial^2 \mathbf{P}_2}{\partial \alpha_i \partial \alpha_j}$$

$$\boxed{\frac{\partial \mathbf{P}}{\partial \alpha_i} = \left(\frac{1}{2\lambda}\mathbf{M} - \frac{1}{8\lambda^3}\mathbf{M}\mathbf{c}\mathbf{c}^T\mathbf{M}\right)\frac{\partial \mathbf{c}}{\partial \alpha_i}}$$

$$\boxed{\begin{aligned}\frac{\partial^2 \mathbf{P}}{\partial \alpha_i \partial \alpha_j} = {} & \left(-\frac{1}{8\lambda^3}\mathbf{M} + \frac{3}{32\lambda^5}\mathbf{M}\mathbf{c}\mathbf{c}^T\mathbf{M}\right)\mathbf{c}^T\mathbf{M}\frac{\partial \mathbf{c}}{\partial \alpha_j}\frac{\partial \mathbf{c}}{\partial \alpha_i} \\ & - \frac{1}{8\lambda^3}\left[\left(\mathbf{c}^T\mathbf{M}\frac{\partial \mathbf{c}}{\partial \alpha_i}\right)\mathbf{M} + \mathbf{M}\mathbf{c}\left(\frac{\partial \mathbf{c}}{\partial \alpha_i}\right)^T\mathbf{M}\right]\frac{\partial \mathbf{c}}{\partial \alpha_j} \\ & + \left(\frac{1}{2\lambda}\mathbf{M} - \frac{1}{8\lambda^3}\mathbf{M}\mathbf{c}\mathbf{c}^T\mathbf{M}\right)\frac{\partial^2 \mathbf{c}}{\partial \alpha_i \partial \alpha_j}\end{aligned}}$$

$$\varepsilon : \frac{x^2}{r_1^2} + \frac{y^2}{r_2^2} + \frac{z^2}{r_3^2} = 1$$

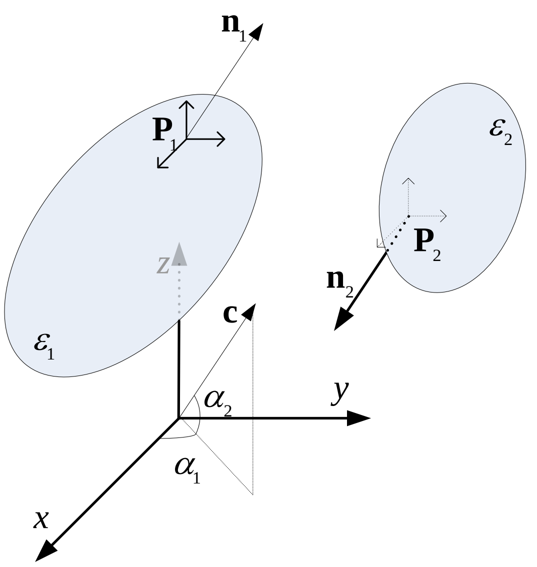
$\mathbf{A}$ **:** Rotation Matrix

$$\mathbf{M} = \mathbf{A}\mathbf{R}^2\mathbf{A}^T$$

$$\mathbf{R} = diag(r_1, r_2, r_3)$$

$\mathbf{b}$ **:** Translation of ellipsoids center

$$\lambda^2 = \frac{1}{4}\mathbf{n}^T\mathbf{M}\mathbf{n}$$



$$\mathbf{d} = \mathbf{P}_1 - \mathbf{P}_2$$

$$\min_{\alpha_1, \alpha_2} \left\| d(\alpha_1, \alpha_2) \right\|^2$$

Collision Detection

- Broad phase
  – Draws on an Axis Aligned Bounding Box (AABB) approach

- Narrow phase
  – Draws on Minkowski Portal Refinement

Assembled Quad GPU Machine

Processor: AMD Phenom II X4 940 Black

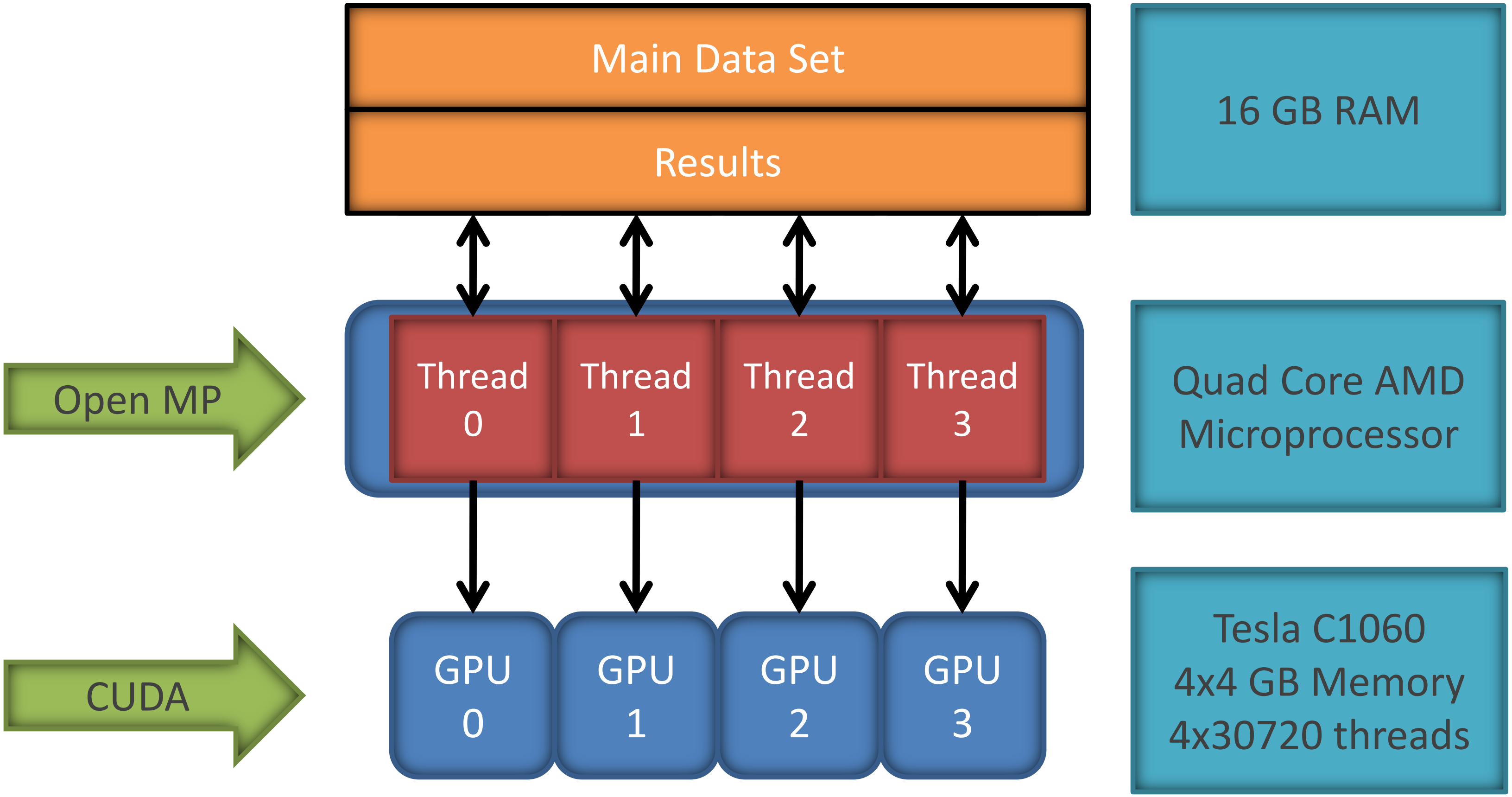
Memory: 16GB DDR2

Graphics: 4x NVIDIA Tesla C1060

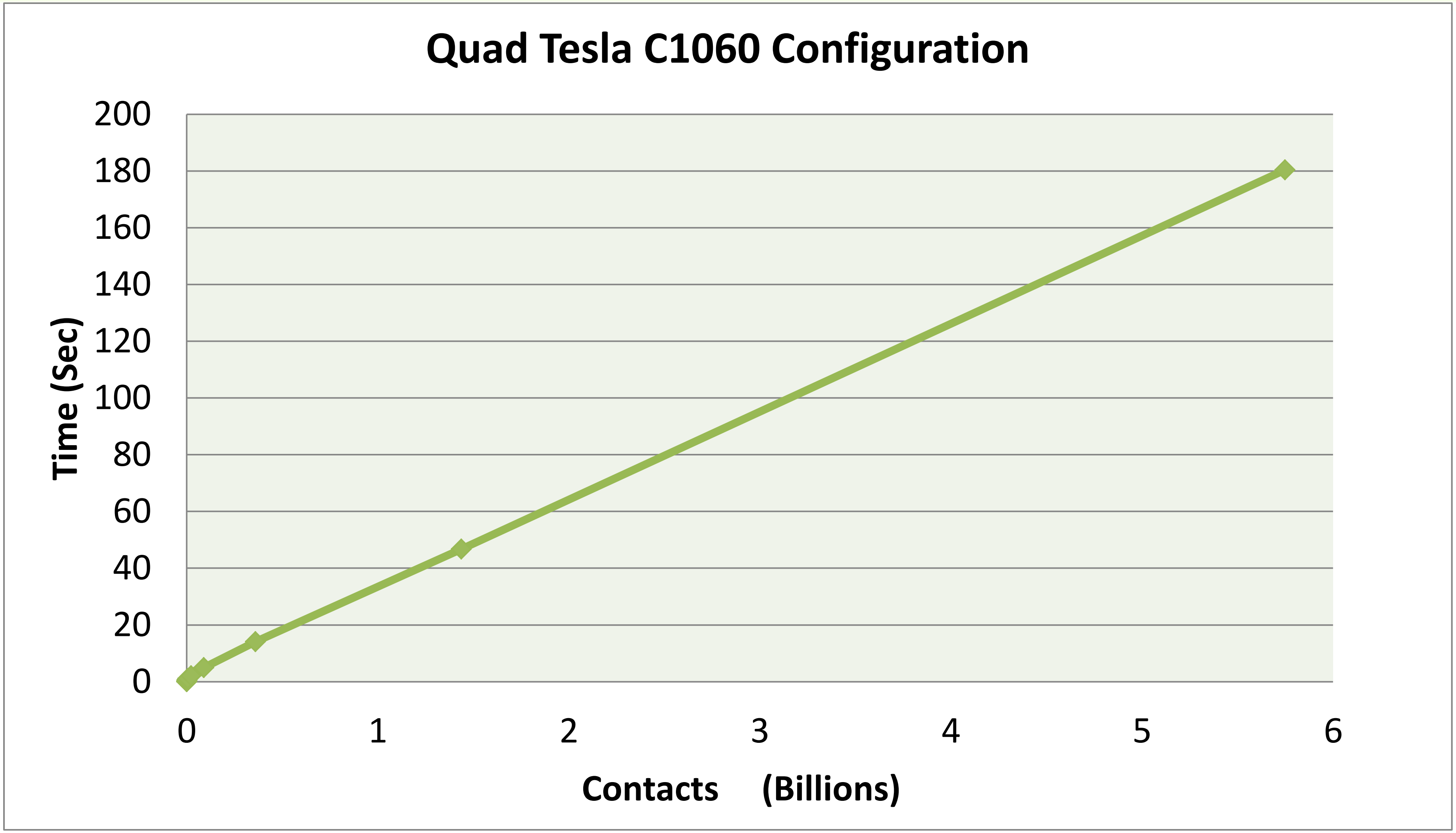
Power supply 1: 1000W

Power supply 2: 750W

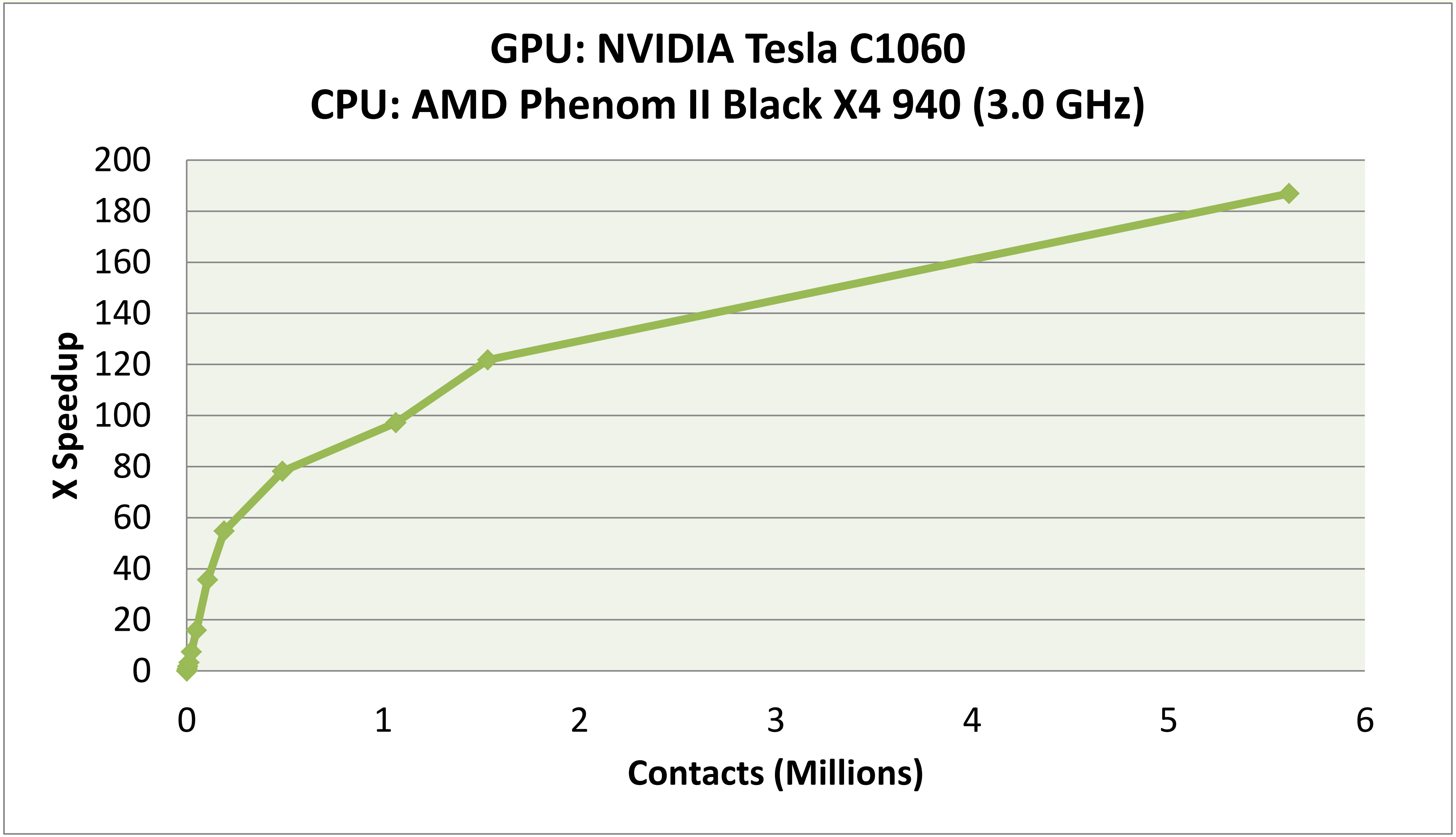
Software/Hardware Setup



Spheres – Contacts vs. Time



Speedup - GPU vs. CPU (Bullet library)
[results reported are for spheres]



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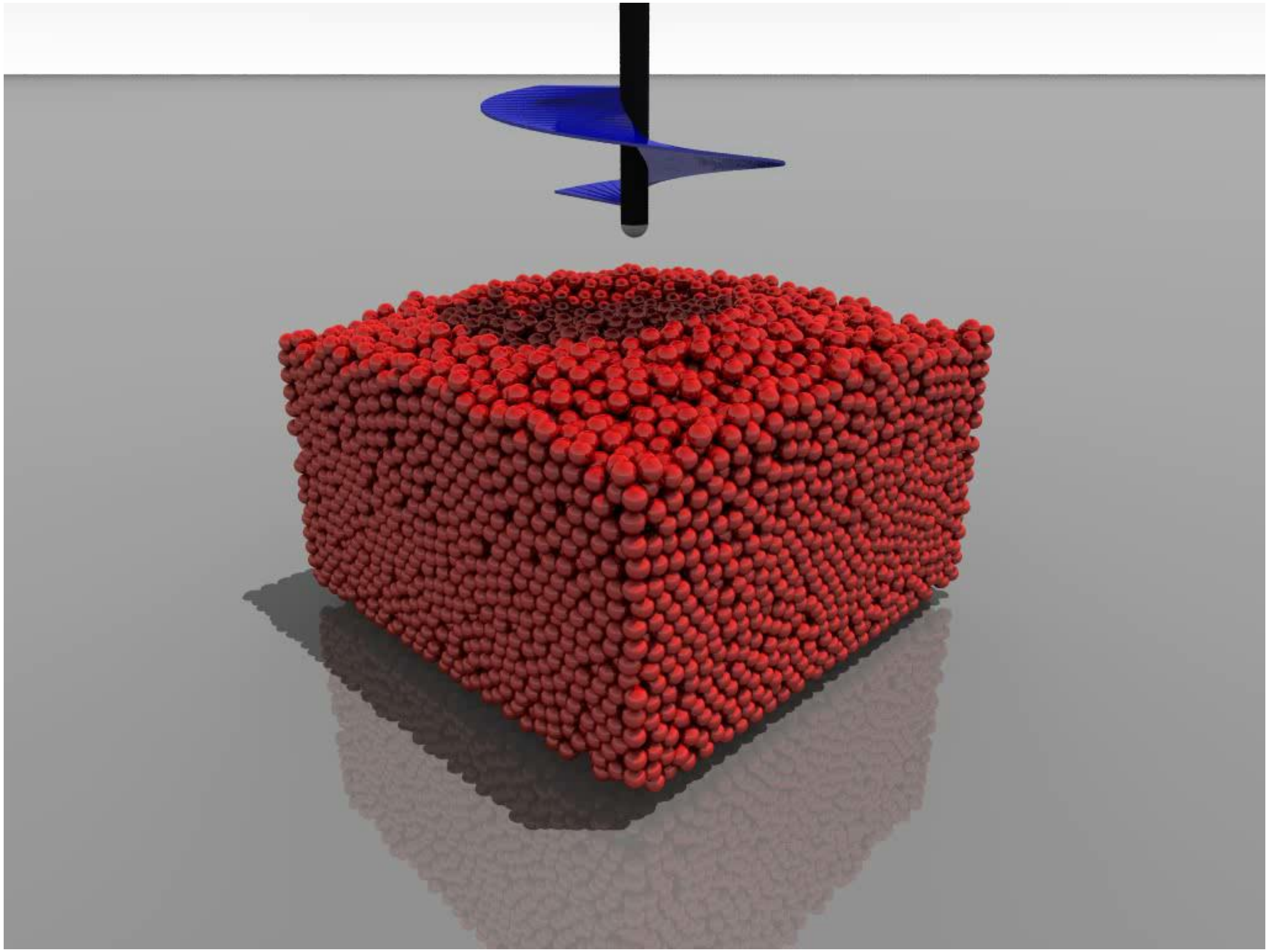
$$h = .0001\ [s]$$

$$g = -9.80665\ \left[\frac{m}{s^2}\right]$$

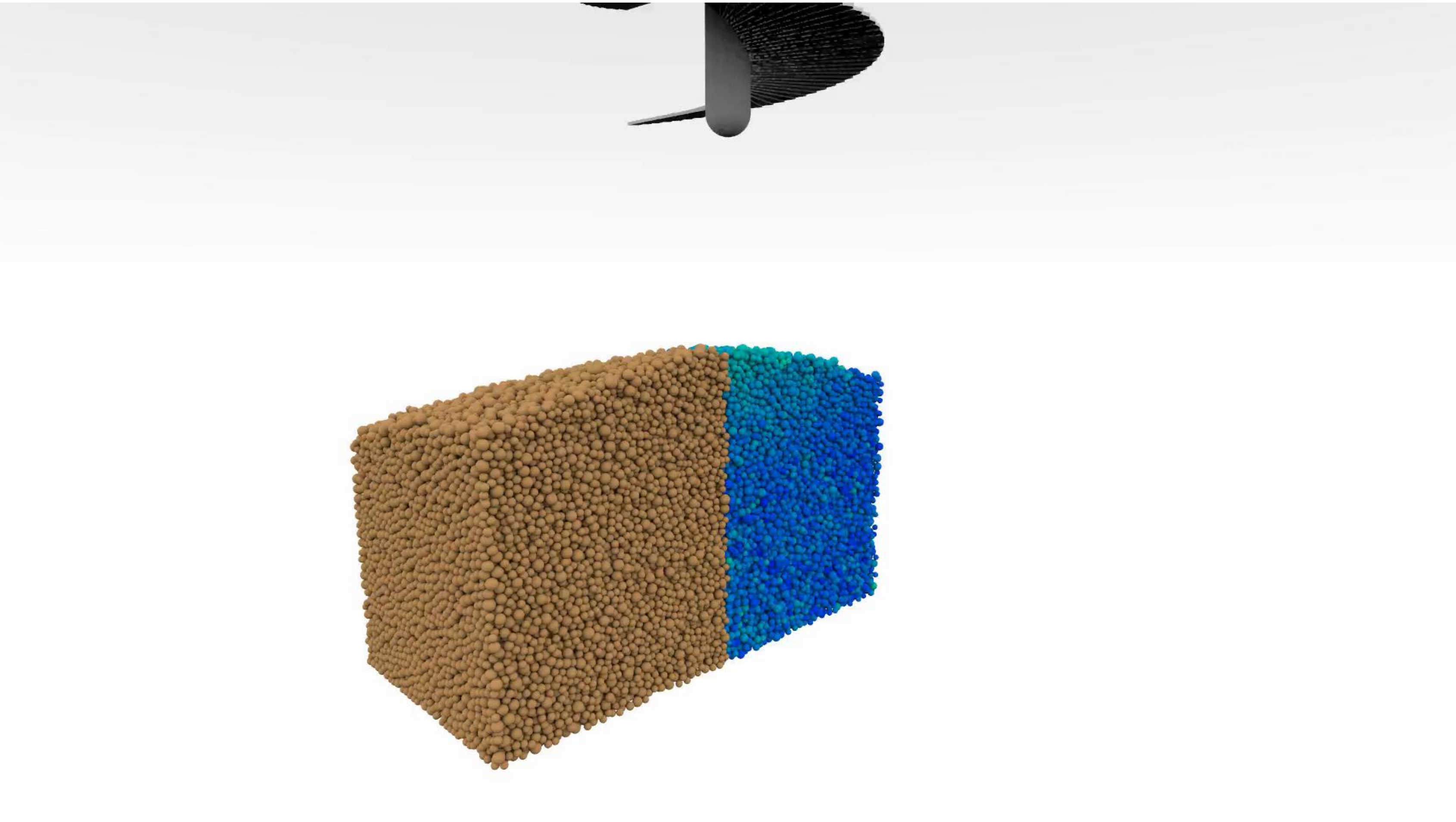
$$20k\ spheres$$
$$r = 3.5\ mm$$
$$\mu = .46$$

$$\omega = \pi\ \left[\frac{\text{rad}}{\text{sec}}\right]$$

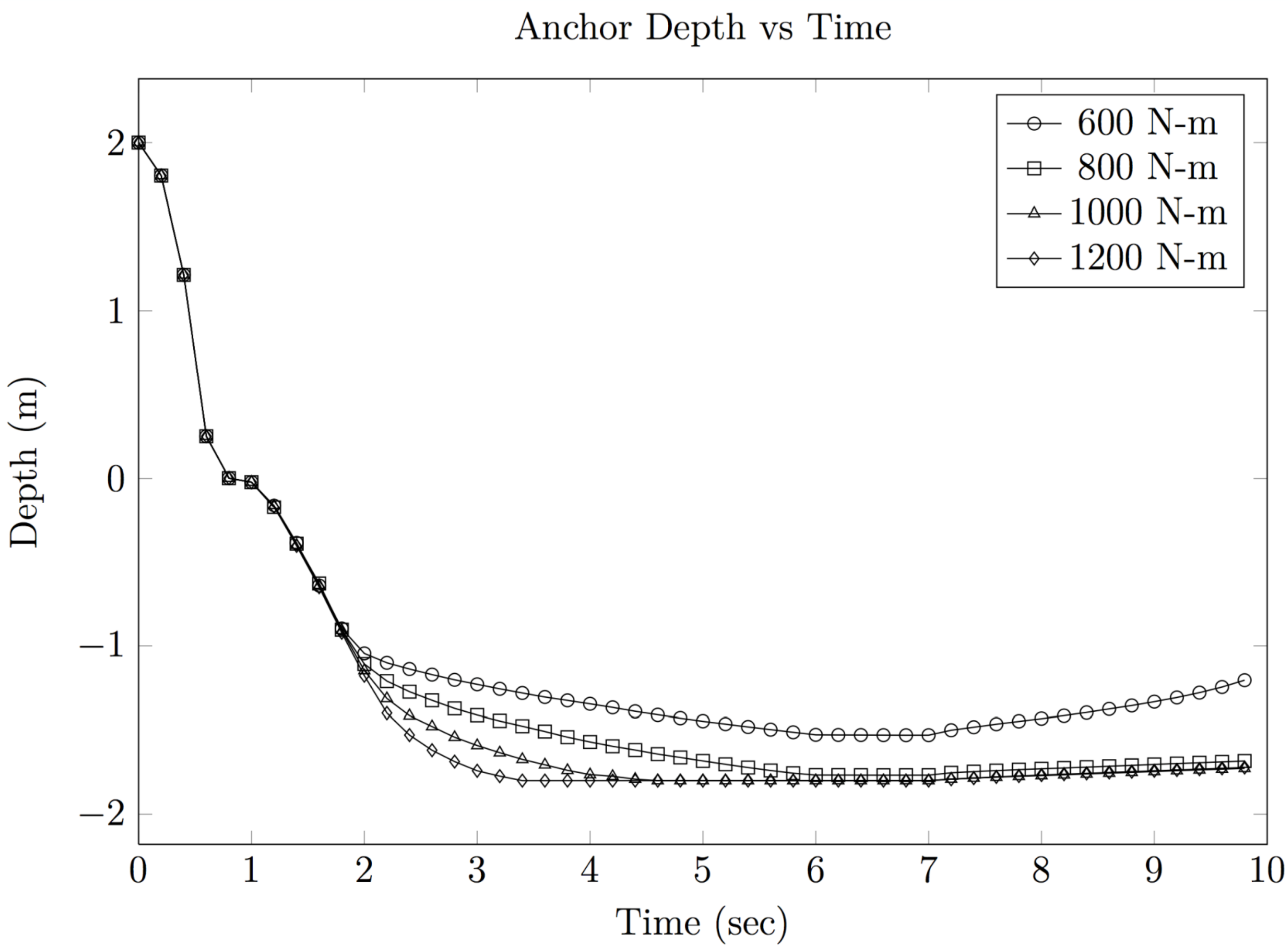
$$Anchor\ width = 5\ [cm]$$



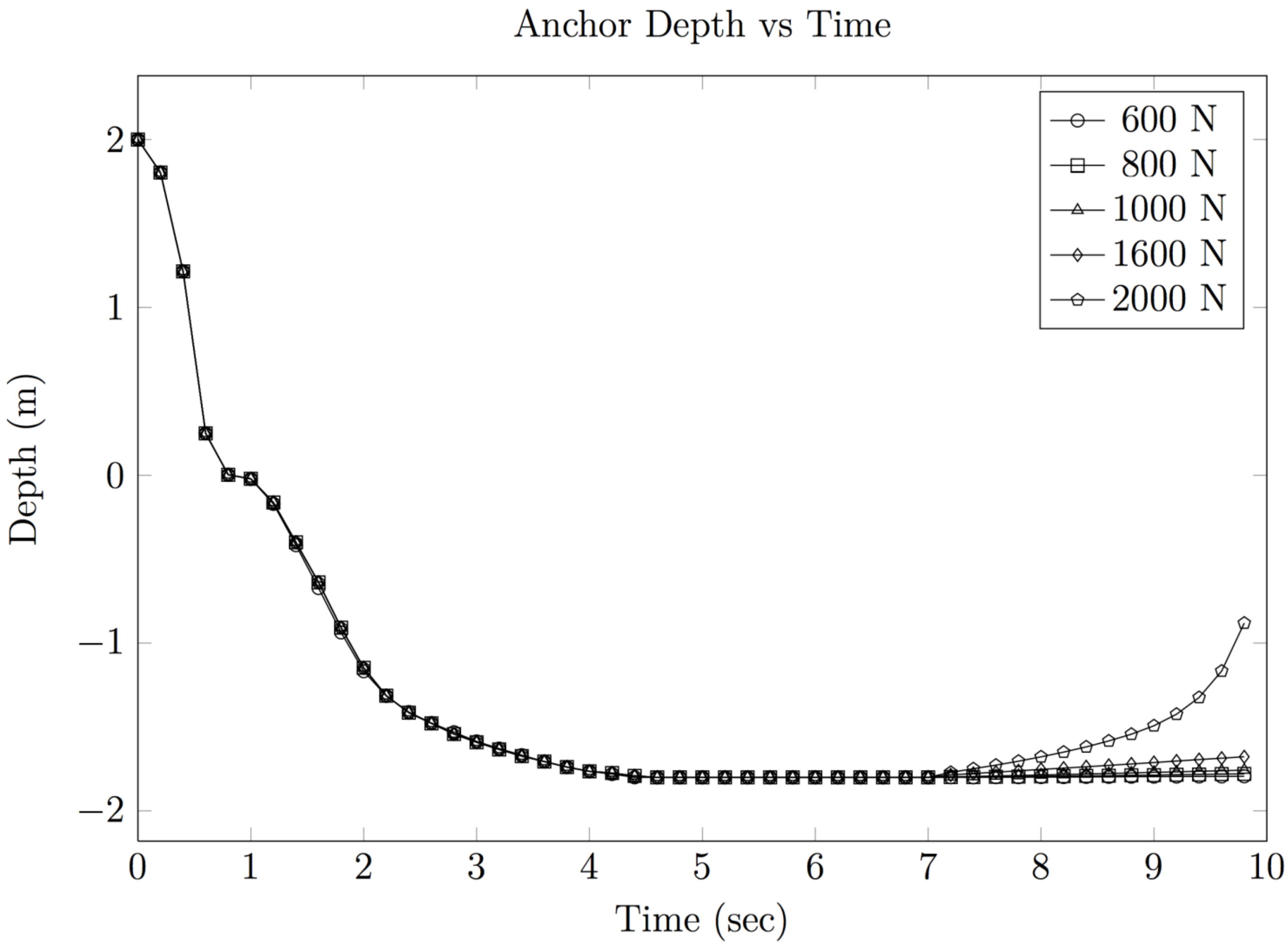
200,000 Bodies & 10 kg Anchor



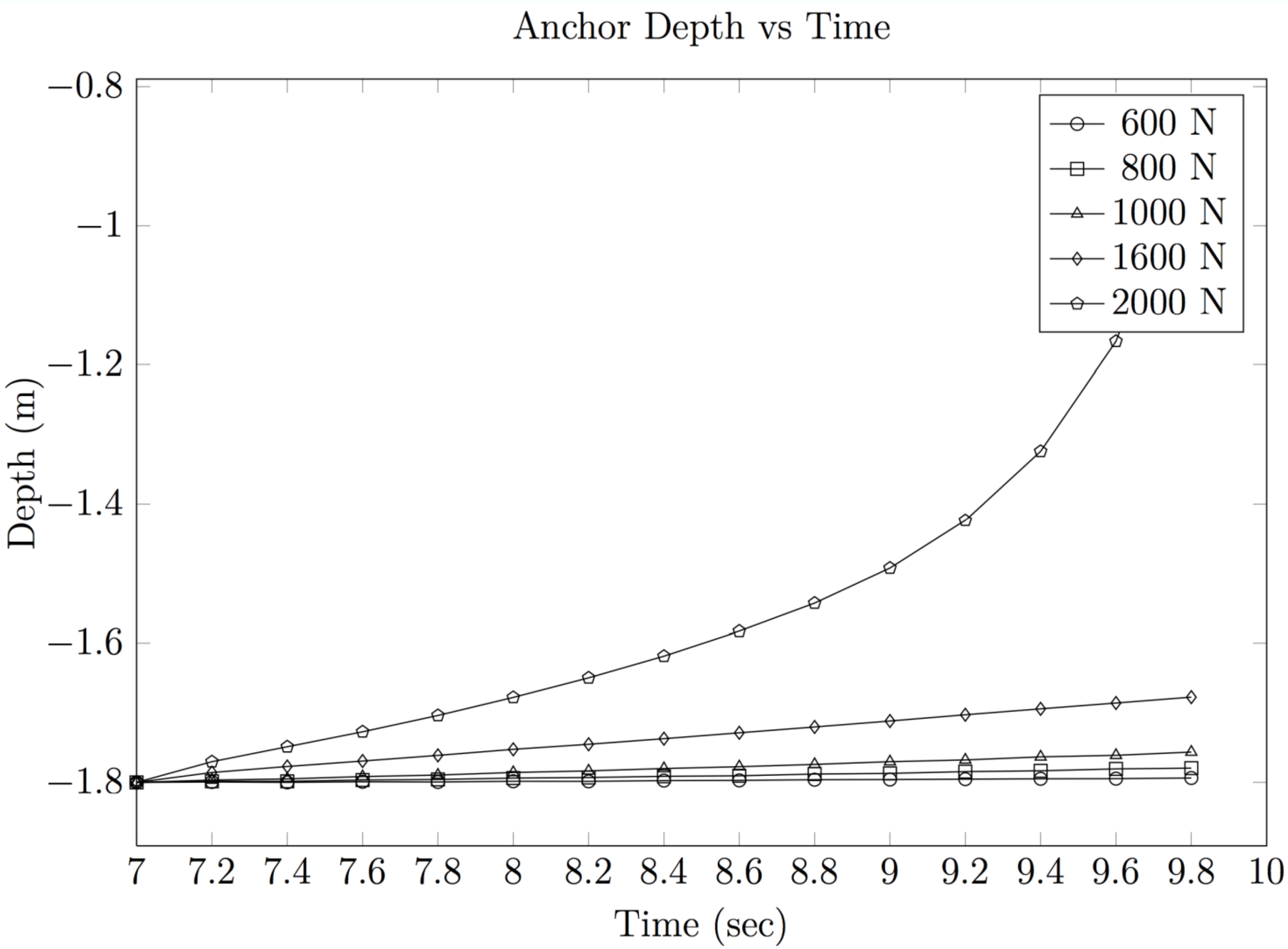
Anchor Penetration Depth, Function of Applied Torque



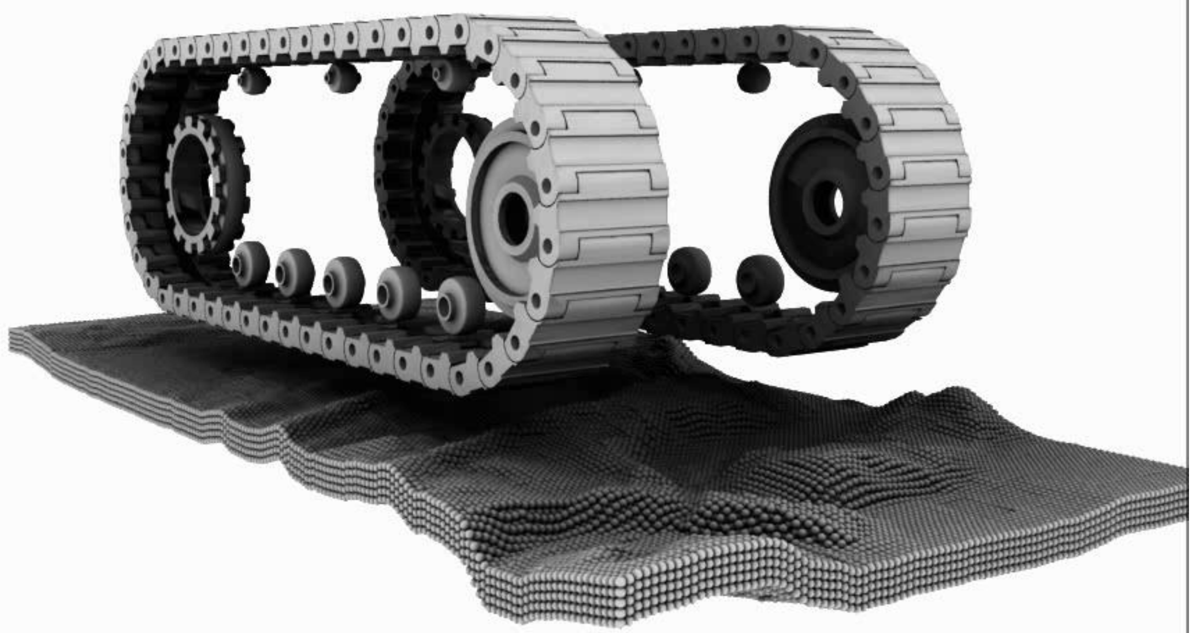
Depth as a Function of Pulling Force



Depth as a Function of Pulling Force



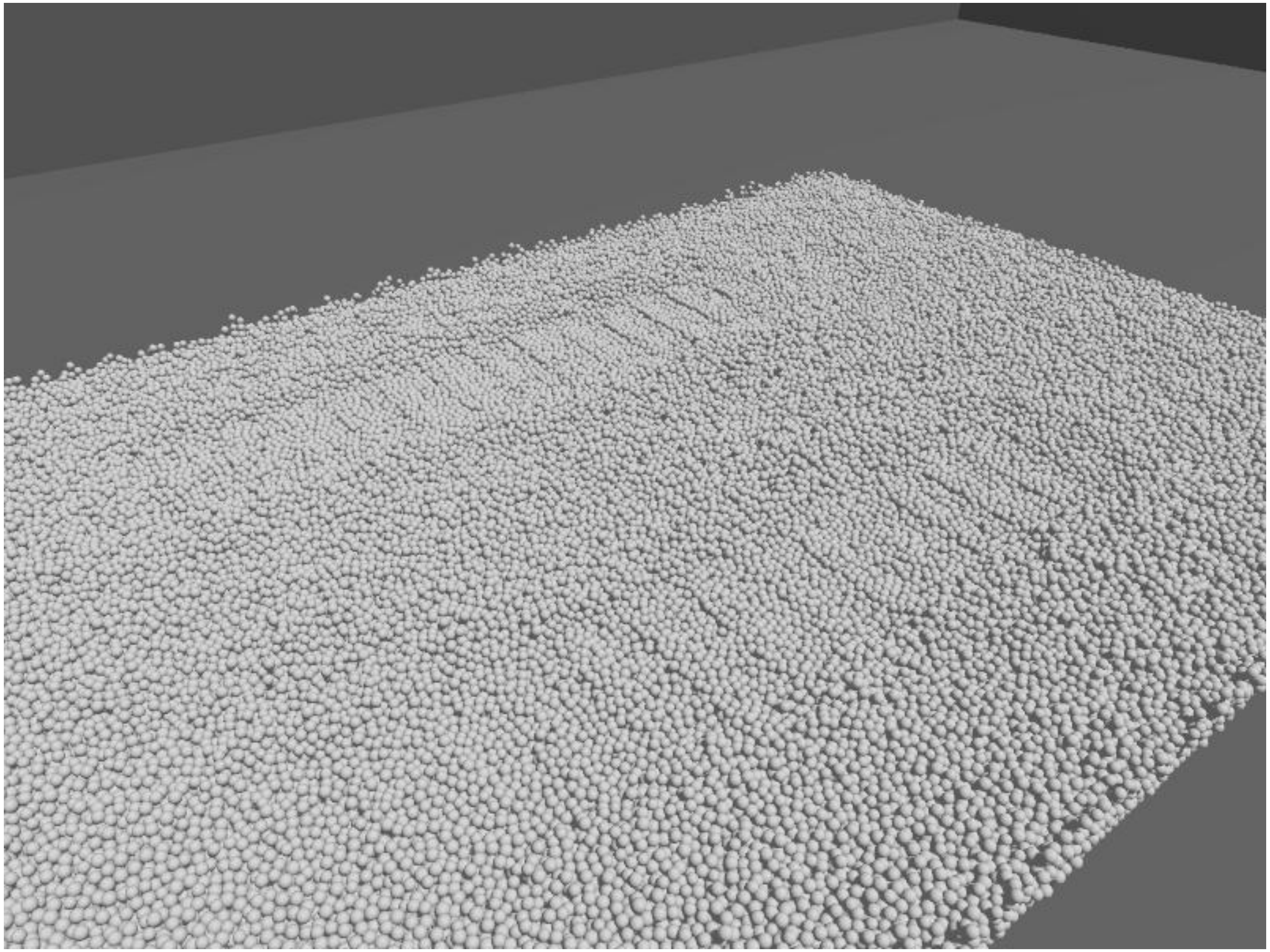
Track Simulation



Parameters:

- Driving speed: 1.0 rad/sec
- Length: 12 seconds
- Time step: 0.005 sec
- Computation time: 18.5 hours
- Particle radius: .027273 m
- Terrain: 284,715 particles
- Inertia parameters of track are fake

Dual Track 'Footprint'

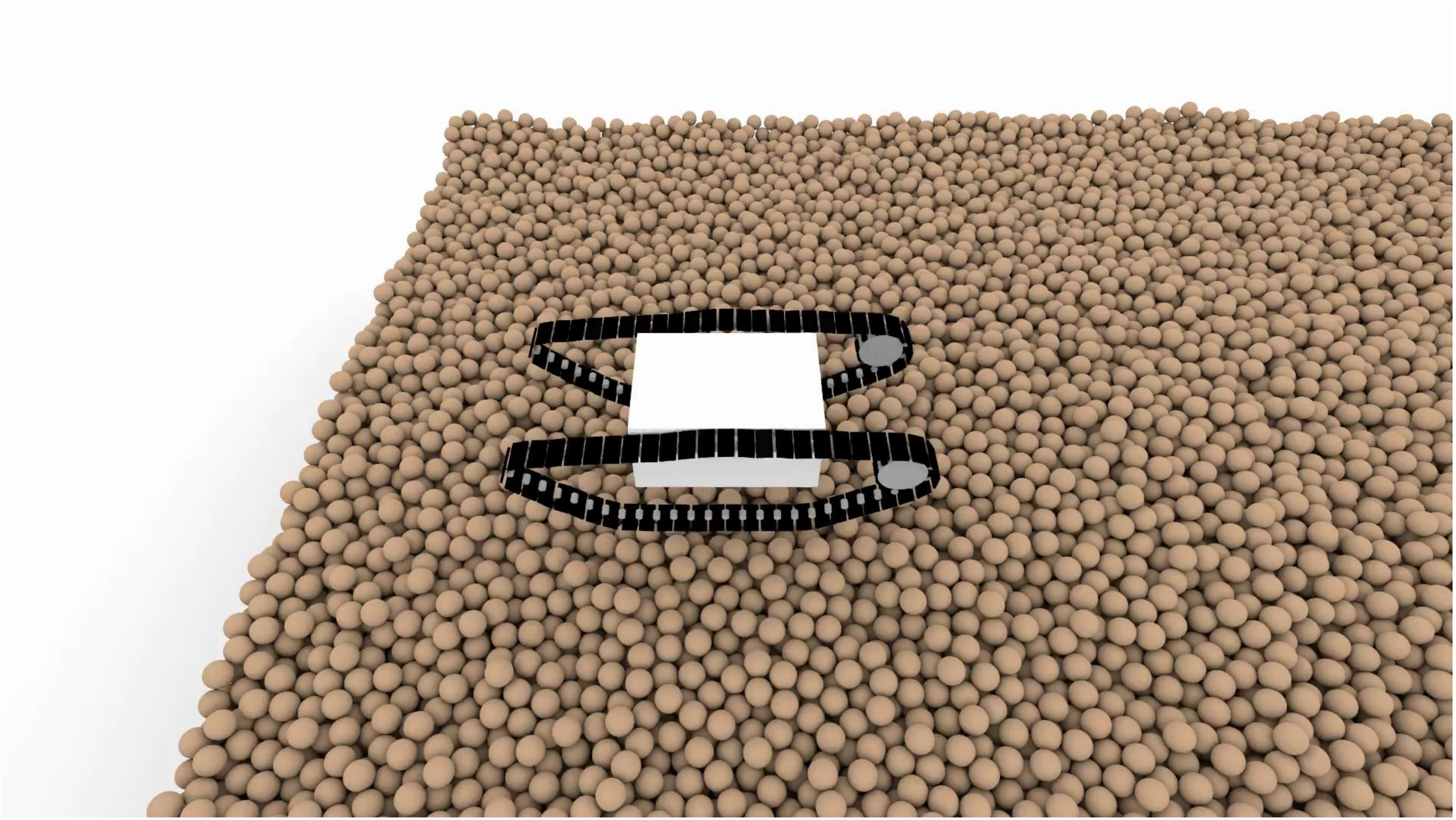


In theory, there is no difference between theory and practice. In practice, there is.

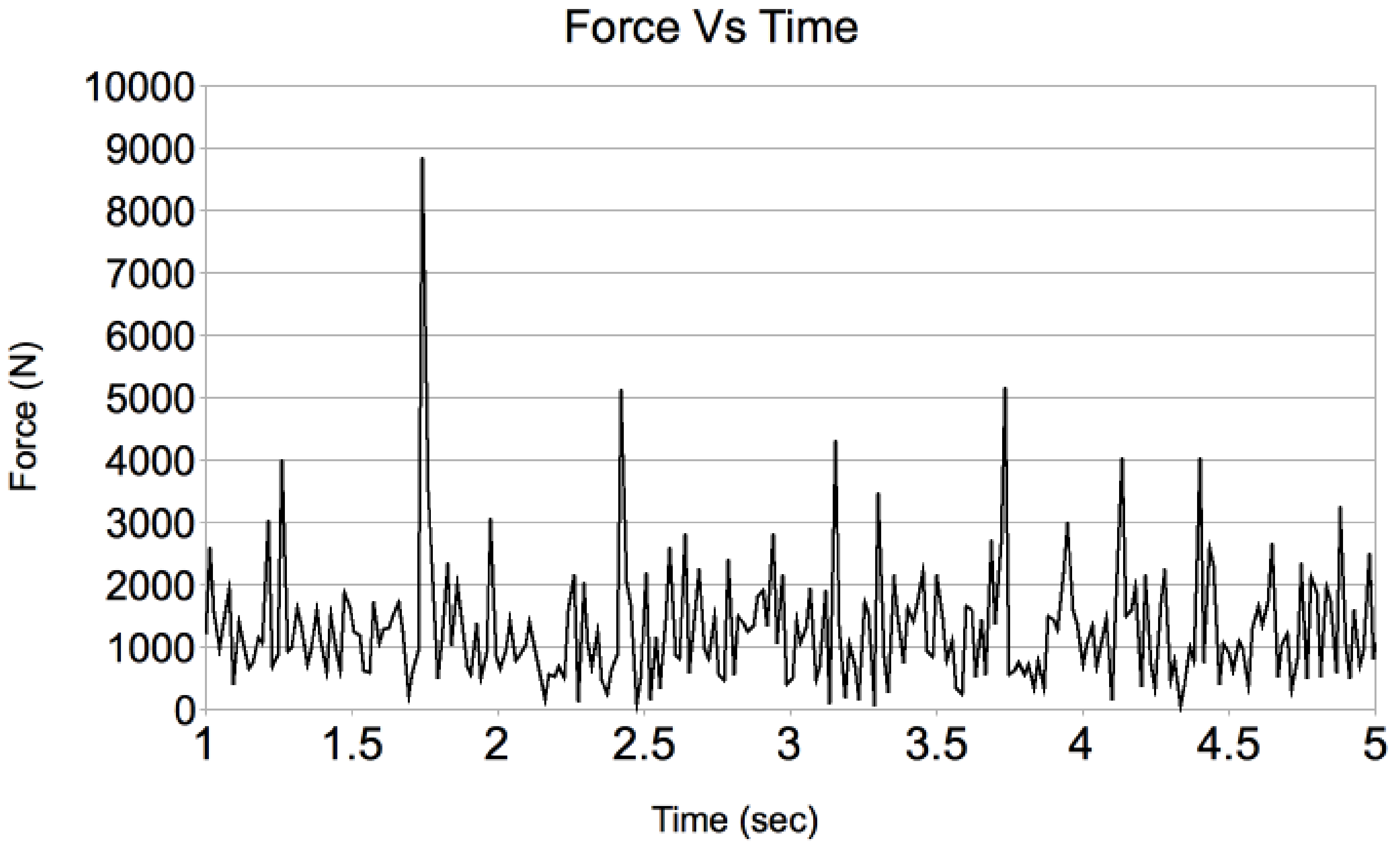
Yogi Bera

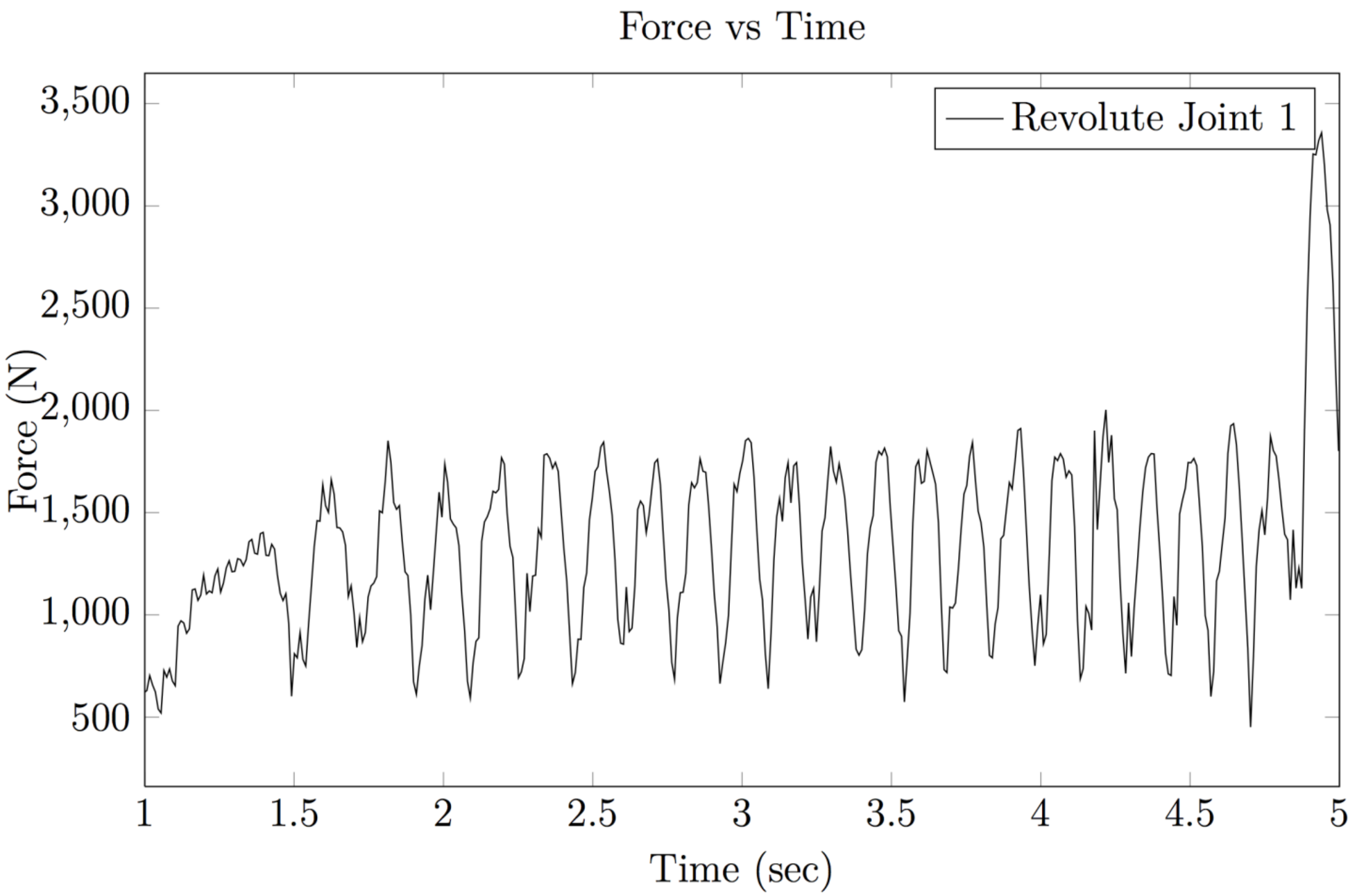
M113 Tank Simulation

Real Masses for Both Obstacles and Terrain…

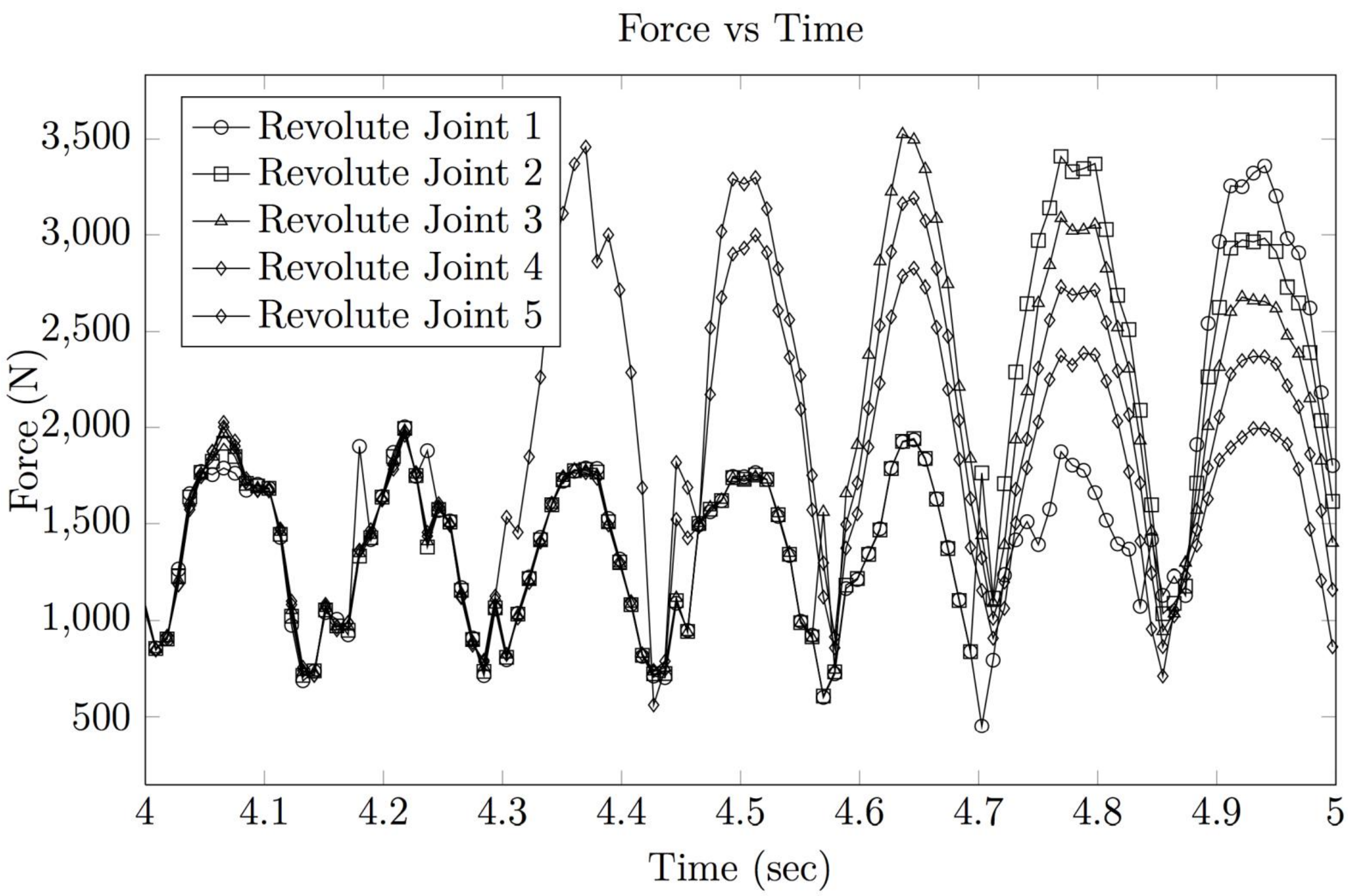


Vehicle-Track-Terrain Interaction




Force vs Time
Revolute Joint 1
3,500
3,000
2,500
2,000
1,500
1,000
500
Force (N)
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

Vehicle-Track-Terrain Interaction



Conclusions/Putting Things in Perspective

- Goal: investigate how computing can catalyze over the next 10 years advances in Science and innovation in Engineering

- Reaching the goal…
  - Develop an experimentally validated Heterogeneous Computing Template (HCT)
  - Use HCT to advance state of the art in physics-based simulation

Details reported in…

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Thank You.

negrut@wisc.edu
http://sbel.wisc.edu
University of Wisconsin-Madison
Simulation-Based Engineering Lab
Wisconsin Applied Computing Center

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